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1. Coherent transients using counterpropagating fields
2. New resonances in cold-atom spectroscopy
3. Laser cooling in one dimension using linearly polarized fields
4. Theory of four-wave mixing

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During the past year, progress has been made in the areas of (1) coherent transients using counter–propagating fields; (2) new resonances in cold–atom spectroscopy; (3) laser cooling in one dimension using linearly polarized fields; and (4) theory of four–wave mixing. Our results are summarized briefly below.

(1) Coherent transients using counter–propagating fields. (B. Dubetsky, T. Sleator, P.R. Berman) We have studied the interaction of a series of counterpropagating pulses with an atomic ensemble of cold or thermal atoms.[1*] In a scheme we refer to as a grating stimulated echo (GSE), the atoms interact sequentially with two counterpropagating pulses, a standing wave pulse and a third traveling wave pulse. The first two pulses create a spatially modified ground state population which dephases as a result of inhomogeneous broadening. The standing wave pulse reverses the direction of the dephasing so that the populations can rephase at some appropriate time after the application of the standing wave pulse. The rephasing is probed by the third traveling wave pulse which leads to an echo signal. The GSE is a very sensitive probe of any velocity changes experienced by the ground state atoms. As such it has potential applications as a probe of collisional processes, a probe of photon recoil effects, and as an accelerometer. Calculations along these lines are in progress. We have also considered a variant of the GSE in which the time delay between the first two pulses is set equal to zero. We have solved this problem in a perturbation theory limit for arbitrary polarizations of the applied fields and arbitrary fine and hyperfine structure. The resulting magnetic grating echo (MGE) signal can be used to determine the various hyperfine splittings. Articles on these results are in preparation.

(2) New resonances in nonlinear spectroscopy. (P. R. Berman, J. Guo, B. Dubetsky) Motivated by recent experiments of Kimble's group[2] and the laser cooling group in Paris,[3] we began a study of the pump–probe spectroscopy and four–wave mixing of cold atoms. For an ensemble of two–level atoms, we predict the existence of a new class of resonances whose origin can be traced to the photon recoil effect. These *recoil–induced resonances* (RIR) appear in the sub–Doppler limit and have a shape which mirrors that of

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the atomic velocity distribution.[4*] As such, nonlinear spectroscopy can be used as a probe of the velocity distributions achieved by laser cooling. The calculation was extended to include effects related to the magnetic degeneracy of the atomic levels, a feature critical to sub–Doppler cooling. We found that the RIR persist even in the presence of optical pumping,[5*] although they may be obscured in some cases by effects related to atomic localization. The narrow structures seen recently in pump–probe spectroscopy of cold atoms[6] may provide experimental confirmation of these resonances.

(3) Laser cooling in one dimension using linearly polarized fields (J. Guo, P. R. Berman) We studied laser cooling in one dimension produced by two, counterpropagating, linearly polarized fields whose polarization angles differ by an amount θ.[7*] Since sub–Doppler cooling is known to exist for $\theta=\pi/2$ and not to exist for $\theta=0$, one might think that there is a monotonic increase in the friction force of laser cooling as θ varies from 0 to $\pi/2$. We have found this *not* to be the case. Instead, for small angles $\theta \ll 1$, the friction force can actually be larger than that for $\theta=\pi/2$. The result is linked to the fact that there is a rapid variation of the atomic population difference density in the vicinity of the quasi–field nodes which occurs for $\theta \ll 1$. A similar feature appears in the two–dimensional cooling of an atomic vapor by two, orthogonal, standing wave fields which are linearly polarized in orthogonal directions. In the 2–D case, the situation is somewhat more dramatic as the friction force actually has a logarithmic dependence on velocity for small velocity.[8*] Our calculations show that "standard" methods for calculating the friction coefficient are doomed to failure for the limiting cases we studied, owing to the rapid variation of population density near the field nodes. Diffusion and particle localization have also been studied for the 1–D case and channeling of the particles in momentum has been studied for the 2–D case.

It was found that the depth of the optical potentials was sufficiently large to allow for localization of the atoms in the minima of the potentials. Thus, our calculations, in which all effects related to atomic localization are ignored, can be questioned. To evaluate the role played by atomic localization, we repeated the calculation using a fully quantized approach. We found that the qualitative conclusions reached for the sub–Doppler cooling on a $J=1/2 \rightarrow 1/2$ transition did not change.[9*] Thus, there is a range of laser field strengths where a lower temperature is reached if one uses an angle $\theta \neq \pi/2$ between the two field polarization vectors. The distribution of populations in the various bands of the optical potential was also studied as a function of θ.

Theory of four–wave mixing using an amplitude approach. (B. Dubetsky, P. R. Berman) A theory of four–wave mixing was formulated using an *amplitude* approach in the Schrodinger picture.[10*] The calculation properly accounts for the repopulation of the ground state of the "two–level" atoms resulting from spontaneous emission. Until this calculation, no one has been successful in developing such a theory. The interplay between the excitation and emission at the various atomic sites is evident in this amplitude approach, which involves fourteen distinct contributions to the final state amplitude. The technique is extended to include effects related to the recoil–induced resonances mentioned above, as well as the so–called pressure induced extra resonances. Surprisingly, the amplitude calculation is actually simpler than the density matrix calculation in certain limits, as the final state probability can be rewritten in an especially simple form.

(5) Miscellaneous. Earlier articles on coherent transients using broadband optical sources[11*,12*,13*], nonlinear spectroscopy and laser cooling[14*], and lasing without inversion in dressed–state lasers[15*] have appeared.

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